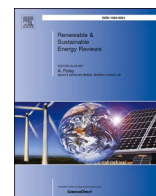




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# How likely is Brazil to achieve its NDC commitments in the energy sector? A review on Brazilian low-carbon energy perspectives

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## ABSTRACT

This paper offers perspectives on the development of low-carbon energy technology in Brazil, pinpointing changes that have occurred since our former publication in 2011. It takes a fresh approach in terms of how likely Brazil will achieve its Nationally Determined Contributions Commitments in the energy sector. Many countries have implemented national climate policies to accomplish their pledged NDC and contribute to the temperature objectives of the Paris Agreement on climate change. Based on official reports and databases of energy development projections in Brazil and the socioeconomic context, we discuss what can be expected for the future of the Brazilian energy sector, the probability of implementing selected technologies, and the prospects of reaching the NDC targets for 2025 and 2030. In addition, this paper provides an overview of the current stage of development of these technologies, main directions, and bottlenecks in Brazil. Analyses have shown that the Brazilian renewable matrix tends to remain significant, driven by the development of solar and mostly small hydroelectric power sources, as well as different types of biomass. In addition, the system will include the replacement of thermoelectric plants powered by diesel and fuel oil by natural gas plants. The prospects for Brazil's official energy plan for 2027 are aligned with the reference technology scenario, which represents the business as usual scenario. Despite this, low-carbon technologies could be implemented far beyond the NDC's goals, given the abundance of renewable natural resources in the country.

## 1. Introduction

The objective of the Paris Climate Agreement is to constrain the average global warming to below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C by reducing emissions. While this objective is formulated at the global level, the

success of the agreement critically depends on the implementation of climate policies at the national level, materialised by the requirement of countries to submit Nationally Determined Contributions (NDCs) [1]. The Paris Agreement foresees cycle reviews of the NDCs every five years, allowing countries to reach their current commitments and expand their ambitions and mitigation goals. Thus, countries are expected to update their NDCs in 2020. The primary methods to reduce greenhouse gas

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Abbreviations			
2DS	2 °C Scenario	OECD	Organisation for Economic Co-operation and Development
AFOLU	Agriculture, Forests and other land use	PAC2 Mobilidade	Urban Mobility Growth Acceleration Programme (in Portuguese, Programa de Aceleração do Crescimento da Mobilidade Urbana)
ANEEL	National Electric Energy Agency (in Portuguese Agência Nacional de Energia Elétrica)	PBE	Equipment Labelling Programme (in Portuguese, Programa Brasileiro de Etiquetagem)
ANP	National Agency of Oil, Natural Gas and Biofuel (in Portuguese, Agência Nacional do Petróleo, Gás Natural e Biocombustíveis)	PEE	ANEEL's Energy Efficiency Programme (in Portuguese, Programa de Eficiência Energética)
B2DS	Beyond 2 °C Scenario	PLANSAB	National Plan for Basic Sanitation (in Portuguese, Plano Nacional de Saneamento Básico)
BNDES	National Development Bank's (in Portuguese, Banco Nacional de Desenvolvimento Econômico e Social)	PNLT	National Plan for Logistics and Transport (in Portuguese, Plano Nacional de Logística e Transportes)
BRL	Brazilian Real (Currency)	PNMU	National Urban Mobility Plan (in Portuguese, Plano Nacional de Mobilidade Urbana)
CBIO	Biofuel Decarbonization Credit (in Portuguese, Crédito de Descarbonização)	PPA	Power Purchase Agreement
CCS	Carbon Capture Storage	PROÁLCOOL	National Alcohol Programme (in Portuguese, Programa Nacional do Alcool)
CNPE	National Council of Energy Policy (in Portuguese, Conselho Nacional de Política Energética)	PROBIOGÁS	Brazil-Germany Project to Promote Utilization Biogas Energy in Brazil (in Portuguese, Projeto Brasil-Alemanha de Fomento ao Aproveitamento Energético de Biogás no Brasil)
CO <sub>2</sub>	Carbon Dioxide	PROCEL	National Programme for Electricity Conservation (in Portuguese, Programa Nacional de Conservação de Energia Elétrica)
CO <sub>2</sub> -EOR	Enhanced oil recovery	PROCONVE	Automotive Pollution Control Programme (in Portuguese, Programa de Controle de Poluição do ar por Veículos Automotores)
CONFAZ	National Council of Finance Policy (in Portuguese, Conselho Nacional de Política Fazendária)	PRODEEM	Energy Development Programme for States and Municipalities (Programa de Desenvolvimento Energético dos Estados e Municípios)
CONPET	National Programme for the Rational Use of Oil and Gas Products (in Portuguese, Programa Nacional da Racionalização do uso dos Derivados de Petróleo e do Gás Natural)	PROINFA	Programme of Incentives for Alternative Electricity Sources (in Portuguese, Programa de Incentivo às Fontes Alternativas de Energia Elétrica)
CSP	Concentrated Solar Power	PV	Photovoltaic Panel
EPE	Energy Research Company (in Portuguese, Empresa de Pesquisa Energética)	R&D	Research & Development
ETP	Energy Technology Perspectives	RENOVABIO	National Biofuels Policy (in Portuguese, Política Nacional de Biocombustíveis)
GDP	Gross Domestic Products	RTS	Reference Technology Scenario
GHG	Greenhouse Gas	SBMT	Sequential Batch Methanation Tunnels
GLP	Liquefied Petroleum Gas	SIN	National Interconnected System (in Portuguese, Sistema Interligado Nacional)
GW	Gigawatt	SINIEF	National Integrated System of Economic-Fiscal Information (in Portuguese, Sistema Nacional de Informações Econômicas e Fiscais)
GWP-100	Global warming potential for 100 years	SIRENE	National Emissions Registry System (in Portuguese, Sistema de Registro Nacional de Emissões)
ICMS	Tax on movement of goods and services (in Portuguese, Imposto sobre Circulação de Mercadorias e Serviços)	Toe	Equivalent ton of oil
IEA	International Energy Agency's	TWh	Ton Watt per Hour
INMETRO	National Institute of Metrology, Quality and Technology (in Portuguese, Instituto Nacional de Metrologia, Qualidade e Tecnologia)	UNEP	United Nations Environment Programme
KW	Kilowatt	UNFCCC	United Nations Framework Convention on Climate Change
Mm <sup>3</sup>	Million cubic meters	WMO	World Meteorological Organization
MME	Ministry of Energy (in Portuguese, Ministério de Minas e Energia)		
Mtoe	Millions of tons of oil equivalent		
MW	Megawatt		
MWh	Megawatt-hour		
MWth	Megawatt thermal		
NDC	Nationally Determined Contributions		
NMG	New Gas Market		
°C	Celsius Degrees		

(GHG) emissions are characterised by the sustainable use of bioenergy, large-scale measures relating to land use changes and forests, and a drastic increase in the global share of low-carbon energy by 2050.

The decarbonization of energy generation is the essential basis upon which we can attain the 2 °C target. While long-term indicators of human-induced climate change reached new heights in 2016 – confirmed as the hottest year on record up to now by the WMO [2], and the last four years were also the warmest of those historically recorded [3] – science indicates that it is still possible to reach this goal, and the rate of deployment of low-carbon technologies in emerging economies

will be essential. The UNEP Emissions Gap Report [1,4], and [5] shows that aggregated NDCs are not yet consistent with the 2 °C objective, meaning that more must be done quickly if countries are to successfully restrain global warming to the threshold defined in the Paris Agreement. Therefore, all countries would need to accelerate the implementation of renewable technologies, while efficiency improvements are especially important in emerging countries (China, India, and Brazil) and fossil-fuel-dependent countries (Russian Federation) [1].

Brazil is responsible for approximately a third of the GHG emissions in Latin America and the Caribbean [6], a third of the region's

population, and a third of the region's GDP [7], and it is, thus, at the centre stage of global climate discussions. The most recent report of the National Emissions Registry System (SIRENE) [8] stated that the most significant share of the 2016 CO<sub>2</sub>eq emissions of 1.3 Gt was derived from Agriculture and Livestock (33.64%), Energy (32.36%), and Agriculture, Forests, and other land use, AFOLU (22.28%).

Brazil pledged an emission mitigation target of 37% by 2025 and 43% by 2030, of its 2005 levels [9]. This includes tangible low-carbon energy goals, such as (i) using renewables to supply 45% of all the energy in the country by 2030, (ii) expanding the use of non-hydropower renewables to 23% of the power mixture by 2030, (iii) achieving 10% efficiency gains over a pre-defined baseline in the electricity sector by 2030, and (iv) stimulating efficiency in urban transport and infrastructure, among other targets [10]. The Brazilian government has strong reasons to embrace climate targets. In particular [11], provides evidence that Brazil is not well prepared to deal with climate change and faces severe climate risks. Prominent risk categories include changes in rural yields, water scarcity throughout vast areas of its territory, energy security (linked to a significant dependency on hydropower in the power sector, and on biodiesel and ethanol—both vulnerable to rainfall patterns [12]), climate-induced diseases, and weather hazards [13,14].

Therefore, Brazilian pathways to achieve its NDC should encompass incorporate low-carbon energy technologies because there is a strong nexus between energy and land use. Furthermore, due to its continental dimension and the continuous supply of agroindustry feedstock, Brazil has both potential and effective capacities to lead the bioenergy market worldwide through the manufacturing and utilization of biofuels. Reducing emissions also represents a significant opportunity to drive sustainable economic development, for example, by strengthening its low-carbon energy sectors to generate jobs and add value [8,15]. In addition [16], cost estimates of the Brazilian NDC are predicted to be only 0.7% of the Brazilian GDP in 2030. Comparing this value with the possible economic consequences of climate change demonstrates that compliance with the NDCs can be economically advantageous.

Since the Brazilian NDC was formulated (2015), the economic recession in recent years has caused the trajectory of the national economy to be lower than projected. With the decreased projected growth rates in energy demand in addition to maintaining the NDC targets, the absolute GHG emissions through 2030 are likely to be reduced. Conversely, the economic recession could reduce deforestation control and lead to increased emissions [17].

Brazil experienced a 47% drop in renewables investments between 2017 and 2018, from 6.2 billion USD to 3.3 billion USD, which was a common trend worldwide [19]. In Brazil, the energy market suffered from the economic downturn, delayed renewable energy auctions [19], and the 19% Real devaluation against the US dollar [20]. Nonetheless, the installed capacity for solar PV rose from 0.935 GW in 2017 to 1.798 GW in 2018, and wind generation was expanded by 17.2%, reaching 14.39 GW [21]. Furthermore, the decreased technology costs associated with renewable energy, primarily photovoltaic cells and modules from China, enable the development of these markets.

A major challenge for the Brazilian energy sector is maintaining a high share of renewable sources in its matrix. For the electricity sector, this implies an expansion predominantly of renewable sources [17]. For the transport sector, it means expanding the production and consumption of liquid biofuels, ethanol, and biodiesel. Another challenge is to increase energy efficiency. These challenges require a variety of energy actions and policies [17].

This paper summarises the wide range of low-carbon energy technologies in Brazil, highlighting significant changes that have occurred since our former publication in 2011 [22]. It also takes a fresh view on the likelihood that Brazil will achieve its NDC commitments in the energy sector. The next section compares the significant sources projecting the advance of the low-carbon energy supply in Brazil, namely the Energy Research Company (EPE), a subsidiary of the Ministry of Mines and Energy and key author of the Brazilian energy plans, and the energy

reports from the International Energy Agency (IEA). These reports were considered by the authors as the most qualified and were available for the purpose of this manuscript due to the scope and methodological consistency of data specific to Brazil that could be compared.

Furthermore, the most significant low-carbon energy technologies for the country are assessed and compared regarding how their perspectives for development have changed since 2011, what factors are behind such changes, and the influences on Brazil's capacity to reach its NDC goals between now and 2030. The fourth section summarises the key findings. Finally, the last section presents the conclusion, research gaps, and future research trends.

## 2. Energy reports for the 2030 horizon: current development perspectives

This section presents an analysis of two important sources of energy data for Brazil. First, the Ten-Year Energy Expansion Plan (in Portuguese, PDE) for 2027 [23] provides updated data of the Brazilian government's most recent integrated efforts to monitor the evolution of the country's overall energy system. The report also considers the long-term policies already set by the government to date. The publication forecasts the energy demand by region and sector, energy supply scenarios by technology and regions, additional generation infrastructure, and efficiency gains.

Similarly, we also analysed the most recent version of the Energy Technology Perspectives 2017 from the International Energy Agency (IEA) [24]. With the support of almost 6000 experts from 53 countries, the IEA seeks to act as a hub for the analysis of energy technologies and policies. The use of these reports is justified by their scope and methodological consistency in the use of data and information, which can be compared with one another, making these instruments the most suitable for the purpose of this article.

### 2.1. Ten-Year Energy Expansion Plan 2027

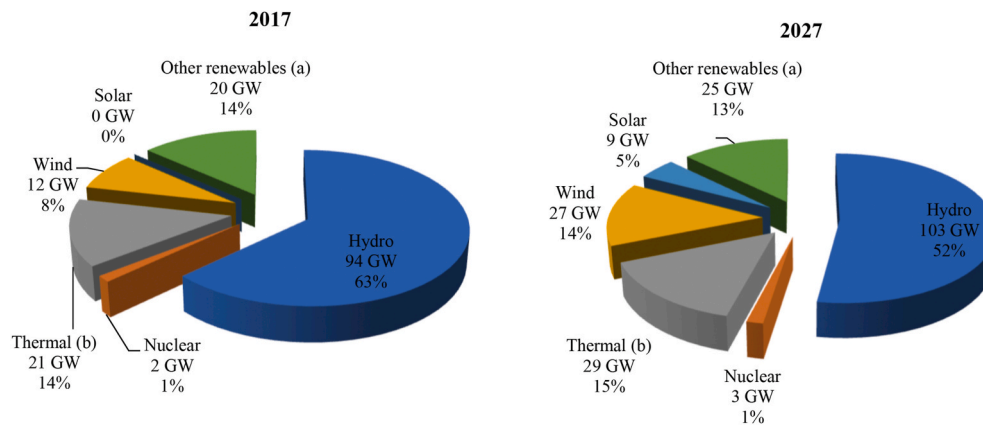
The Ten-Year Energy Expansion Plan 2027 [23] was launched in 2018, projecting the energy trends from 2017 to 2027. The report considers an average GDP growth of 2.8% (although the actual average GDP had decreased between 2014 and 2017) and a total of BRL 1.8 trillion in energy-sector investments between 2018 and 2027. The plan foresees renewables rising in their relative participation in the Brazilian energy mix from 43% in 2017 to 47% by 2027 [23], which is in line with the NDC target.

In the power sector, renewables are expected to maintain their share of installed capacity, as shown in Fig. 1. Although projections show a change from 86% in 2018 to 79% in 2027, the share of renewables will remain high, due to an additional 14 GW of wind power generation capacity, 9 GW in new solar PV capacity, 10 GW in new hydropower dams, 10 GW from new natural gas plants, and an additional 1-GW nuclear unit. Non-hydro renewables (which include small hydro, biomass, wind, and solar) are expected to grow from 22.2% in 2018 to 28% in 2027, surpassing the 23% target set in the NDC for 2030.

Despite their decreasing share in the final consumption matrix, oil products will remain significant, from 41% (107 Mtoe) in 2017 to 39% (127 Mtoe) in 2027, as shown in Table 1. Part of its potential market share is expected to be reduced by the increase in ethanol (from 27.5 Mm<sup>3</sup> to 42.3 Mm<sup>3</sup>), especially in the transportation sector.

Individually, the most important renewable fuels in terms of final energy consumption over the decade are biodiesel (12.2% per year), ethanol (4.3% per year), and black liquor<sup>1</sup> (3.6% per year). Biodiesel demand, driven by the regulation mandating a steady mix of 10% biodiesel in all fossil diesel sold in Brazil [25], is expected to grow from

<sup>1</sup> Originated from pulp production process, which is still widely used for electricity self-production.



**Fig. 1.** Power energy capacity by energy source. (a) Includes generation of Small Hydro, Biomass and Biogas. (b) Thermal: Includes natural gas, coal, fuel oil and diesel generation, industrial gas [23].

**Table 1**

Main forecast points of Ten-Year Energy Expansion Plan 2027.

Energy Matrix	2017	2027
Non-renewable sources	57.0%	53.0%
Renewable sources	43.0%	47.0%
<b>Power Energy Capacity (GW)</b>	<b>2018</b>	<b>2027</b>
Hydro	94.0	103.0
Nuclear	2.0	3.0
Thermal	21.0	29.0
Small Hydro + Biomass + Wind + Solar	32.0	61.0
<b>Energy Efficiency</b>	<b>2017</b>	<b>2027</b>
Consumption without conservation (Mtoe)	248	308
Energy conservation (Mtoe)	1	19
Energy conservation (%)	0.4%	6.17%
Consumption with conservation (Mtoe)	247	289
<b>Electric Efficiency</b>		
Consumption without conservation (TWh)	546,000	794,000
Energy conservation (TWh)	3,000	41,000
Energy conservation (%)	0.55%	5.16%
Consumption with conservation (TWh)	543,000	753,000

Source: Authors' analysis based on forecasts presented in Brazil's latest 10-year energy plan [23]. Note: Depending on the capacity factor for each electricity source, the electric production/consumption will vary.

9.8% in 2018 to 16.0% in 2027. Ethanol follows a similar pathway, with an drastic final consumption increase due to hydrous ethanol (7.4% per year) to be used primarily in combustion engines.

Considering all the fossil fuels, natural gas remains at 7% of the final energy consumption matrix in the projections for the decade [23]. Although a significant part of the Brazilian natural gas consumption has been associated with electricity generation when there are no hydrologically favourable conditions, optimistic economic scenarios are expected to positively affect natural gas consumption, especially in industry, as well as energy or raw material input.

The Brazilian natural gas sector is characterised by a high concentration and verticalization under the control of Petrobras, which has made significant investments in the energy sector within the natural gas chain since 2016. This investment reduction accentuated the need for a new design of the natural gas market in order to develop an environment conducive for investments, which promotes competition from several other players. Among the advances resulting from the initiative, it is important to highlight SINIEF n. 3/2018 [26] from the National Council of Finance Policy (CONFAZ), which modified the tax treatment from the ICMS (taxes on goods and services) related to gas transportation. With this change, the ICMS no longer focuses on the physical flow and began to consider the contractual flow of natural gas transported through pipelines. This change was fundamental and will allow greater efficiency and dynamism for the natural gas market in Brazil. Finally, in July 2019,

the government created the New Gas Market Program (NMG), which aims to promote the opening of the natural gas market in Brazil with the creation of a committee, possibly through 2021.

The Plan also foresees energy and electric efficiency gains, as shown in Table 1. In particular, in the year 2027, the estimated amount of energy efficiency is 6.2% and electrical efficiency is 5% from the specific demand, with substantial savings occurring in the industrial and transport sectors. Differing from the contribution from the sectors to the Brazilian NDC, which are 8% and 10% by 2030, respectively.

## 2.2. Energy Technology Perspectives report

The Energy Technology Perspectives (ETP) report from the International Energy Agency [24] considers three key scenarios for the global energy sector development. The reference technology scenario (RTS) considers the current commitments of countries to limit emissions and improve energy efficiency, including the NDCs pledged under the Paris Agreement. This scenario results in an average temperature increase of 2.7 °C by 2100. The 2 °C Scenario (2DS) establishes an energy system pathway and a CO<sub>2</sub> emissions trajectory consistent with at least a 50% chance of limiting the average global temperature increase to 2 °C by 2100. The Beyond 2 °C Scenario (B2DS), in turn, considers how far the deployment of technologies that are already available or in the innovation pipeline could take us beyond the 2DS. This scenario is consistent with a 50% chance of limiting future average temperature increases to 1.75 °C.

Basically, in the 2DS, the primary energy demand is limited to a 17% growth by 2060 compared with the 2014 levels (ETP's baseline) and is approximately 20% lower than in the RTS. In addition, global emission reductions of 40% in the 2DS by 2060 in comparison with RTS are primarily attributed to increased efficiency (40%), the use of renewables (35%), the deployment of Carbon Capture Storage (CCS) technologies (14%), and an increased use of nuclear energy (6%) [24].

Specifically, for Brazil, the ETP report [24] foresees similar differences across the three scenarios, with 6% and 2% less primary energy demand and 23% and 14% less emissions in 2025 in the B2DS and 2DS, respectively, when compared with the RTS. Within Brazil's power sector, the IEA highlights a major role in onshore wind energy capacity, reporting soaring increments of 460%, 380%, and 400% for the RTS, 2DS, and B2DS, respectively, compared with 2014. Biomass and waste-fired power plants are also expected to affect the decarbonization of the grid, with the installed capacities increasing by 64% in the RTS and 2DS and 82% in the B2DS in 2025.

Considering the RTS, onshore wind energy has the largest capacity increase between 2014 and 2025, from 5 GW to 28 GW, followed by biomass and waste-fired plants increasing from 11 GW to 18 GW, solar PV from 0 GW to 9 GW, and nuclear from 2 GW to 3 GW. Table 2



synthesises the ETP's key forecasts for Brazil's power sector in the RTS, 2DS, and B2DS [24].

For the transport sector, the ETP report forecasts an increased penetration of biofuels between 2014 and 2025, with consumption increasing by 28% and 44% in the 2DS and B2DS, respectively. However, electricity is increased only in the B2DS scenario (23%).

A comparison between IEA [23] and EPE [24] report's reveals that the latter study shows projections for 2027, which are more aligned with the IEA's RST forecasts for 2025 when considering the total energy supply. Table 3 compares the share of renewables in the total energy demand and in the installed power generation capacity for each technology for [23,24].

### 3. Perspectives for selected low-carbon technologies in Brazil

The use of renewable energy, such as wind, solar, and co-generation, for electricity production has grown considerably in Brazil. The growth of wind power generation was a result of the investment initiated by public policies to promote the Brazilian wind industry through the Programme of Incentives for Alternative Electricity Sources (PROINFA in Portuguese) since 2002 [27]. The public and private initiatives in the solar energy segment reflect the creation of a solar photovoltaic industry within the country and the consequent expansion of this energy usage. Therefore, the diversification of the energy matrix is a critical goal. Therefore, new development strategies should focus on higher investments in mostly low-carbon infrastructure due to the huge potential of renewable energy resources in Brazil [28].

The Brazilian employment numbers in renewable energy are an interesting indicator of the sector trends, showing a 4.5% increase in 2018, from 1,076,000 to 1,125,000. As shown in Table 4, it is estimated that more than one million jobs were created directly and indirectly in this sector between 2017 and 2018. The agricultural supply chain is the primary employer in the biofuel sector, with 74% of the total, even with the increasing mechanisation in the fields. The biodiesel operations more than offset the job losses in ethanol production. Hydropower is the second highest employer, with 18% of the renewable energy sector jobs. Wind power, solar PV, and solar thermal combined reach just over 8%, with similar numbers in 2017.

Moreover [8], shows that an activity shift from coal extraction, oil refining, and carbon-intensive manufacturing industries to service sectors, such as the provision of health and education or the tourism-related industries, may not only be positive in terms of job-creation but also contributes to the achievement of the Brazilian NDC goals. According to Ref. [28], Brazilian GHG emission reductions in the AFOLU, renewable energy, and energy efficiency sectors may counterbalance the growth of energy-related emissions through 2030 and help achieve the NDC targets.

This section presented updated detailed information regarding the main energy sources in Brazil. Official data from the National Agency of

**Table 2**  
Brazilian power installed capacity in RTS, 2DS, and B2DS scenarios (GW).

Power generation capacity (GW)	2014	2025		
		RTS	2DS	B2DS
Oil	8	8	8	8
Coal	4	4	4	4
Natural gas	15	15	15	15
Nuclear	2	3	3	3
Biomass and waste	11	18	18	20
Hydro (excl. Pumped storage)	89	114	115	114
Wind onshore	5	28	24	25
Wind offshore	0	0	0	0
Solar PV	0	9	8	8
Concentrated Solar Power - CSP	0	0	0	0
<b>Total</b>	<b>134</b>	<b>198</b>	<b>196</b>	<b>198</b>

Source: Adapted from Ref. [24].

**Table 3**

Technology shares in total energy mix and in power generation capacity across the PDE 2027 and IEA's ETP 2017.

	PDE	ETP		
	2027	2025		
		RTS	2DS	B2DS
Total energy mix (%)				
Non-renewables	53	54.2	47.8	46.0
Renewables	47	45.8	52.2	54.0
Power generation capacity (%)				
Hydropower	52.8	57.3	59.0	57.9
Nuclear	1.7	1.5	1.5	1.5
Fossil-powered thermal plants <sup>a</sup>	14.6	13.6	13.8	13.7
Biomass <sup>b</sup>	8.4	9.0	9.2	10.2
Small Hydro	4.5	–	–	–
Wind onshore and offshore	13.6	14.1	12.3	12.7
Solar PV	4.4	4.5	4.1	4.1
Total	100.0	100.0	100.0	100.0

Notes.

<sup>a</sup> Includes natural gas, coal, fuel oil, and diesel oil.

<sup>b</sup> Considers biomass plus biogas. Source: Prepared by the authors based on [23,24].

**Table 4**

Estimated jobs created by the renewable energy sector in 2018.

Renewable energy sector	Estimated Direct and Indirect Jobs
Solar PV	15,600
Liquid biofuels	832,000
Hydropower	203,000
Wind power	34,000
Solar thermal heating/cooling	41,000

Source: 2017–2018 data from Ref. [19].

Electric Energy, the Brazilian Energy Research Company, and the Renewable Energy Policy Network for the 21st Century were the main sources consulted. Additional data sources regarding specific energy sectors and several scientific articles were also used.

#### 3.1. Hydropower

The Brazilian energy production matrix is mostly comprised of hydroelectric plants, which generated 81.9% of the production in 2011 [29]. Between 2011 and 2015, a severe water crisis altered the hydrological cycle, causing a reduction in the volume of the plant reservoirs. Since then, the country has invested in diversifying its electricity matrix [27].

Currently, Brazil's 1347 hydropower plants have a combined capacity of 105.9 GW, equivalent to 64% of Brazil's installed power generation capacity [30], a 36% increase in generation capacity since the publication of [22]. Less than half of the country's total hydro potential, estimated at 260 GW, has been explored [31]. However, 40% of the unused resources lie within river basins of major environmental and ethnical significance in the northern states, such as Amazonas and Tocantins. Therefore, hydropower developments have been under considerable criticism during the past decade due to the vast environmental and social impacts, for example, the notorious Belo Monte Dam, decreasing the likelihood that Brazil will explore much more of this potential. Alternatives to large hydropower dams have emerged, such as small hydro dams and run-of-the-river plants, with Belo Monte being converted into the latter. Such alternatives are likely to be a key part of Brazil's quest to deliver its NDC.

In particular, small hydropower plants have been on the rise. Since 2011, their installed capacity increased by 46%, reaching 5.2 GW in 2019 [30,32]. Small hydro projects have been developed mostly in the Southeast, Midwest, and South regions near to the consumption centres. In addition, small hydro is highly competitive with financial

opportunities such as the probable adoption of hourly pricing and possible compensation for power [23].

Therefore, small hydro is a vital component to reach the Brazilian NDC in the energy sector, which would help achieve the necessary growth of 4.4%.<sup>2</sup> As mentioned, the construction of new large hydroelectric plants is unlikely, although considerable potential water resources in the country remain unexplored. In addition, expansion through small plants provides an increase in the supply of electricity, ensuring the consistent energy needed to compensate for the intermittency of other alternative energy sources. These facilities also allow for the seasonal complementarity between wind and water sources that occurs naturally in some Brazilian regions, increasing the efficiency of the system [33–36].

However, this expansion must consider situations where small hydro may have greater negative impacts than positive ones, mainly when the socio-environmental issues and other multiple uses of the water resources are not dimensioned and integrated. It is important to consider the synergistic and cumulative environmental impacts resulting from the concentration of small hydro plants within the same river [35].

### 3.2. Bioenergy

According to the NDCs' goals, an increase in the share of bioenergy in the Brazilian energy matrix is projected to be approximately 18% by 2030. Therefore, for more detail, this section was subdivided according to the specific uses for the sectors served: electric, transportation, residential, and industrial.

#### 3.2.1. Bioelectricity

Brazil is the third-largest producer of bioelectricity globally and the largest producer in South America [19]. A significant share of Brazil's solid biomass is converted into bioelectricity, fuelling 8.6% of the country's power generation capacity (14.8 GW in 2019) [30]. Most bioelectricity generation is from sugarcane bagasse, residues from the sugar-energy industry, which has potential for use in the production of electricity in the National Interconnected System (SIN in Portuguese) and has been shown to be highly competitive [23].

The unrealised bioelectricity potential could push this capacity up to 16.5 GW by 2027, primarily by tapping into the opportunity within sugarcane mills. Sugarcane bagasse provides virtually all of the ethanol and meets the power and heat demand of the sugar industry, but it could provide substantially more electricity (and heat) to the grid if this biomass were utilised to its full potential in efficient units. Progress in this sector, however, is slow due to numerous barriers [38]. Only 17.4% of all sugarcane bagasse by-products are currently utilised for power generation, indicating that there is a significant opportunity for growth to achieve the PDE's 16.5 GW bio-electricity capacity target in 2027 [23].

Furthermore, the promulgation in December 2017 of the National Biofuels Policy (RenovaBio) indicated the efficiency requirements of sugar-energy production units may be increased. Consequently, the environmental energy efficiency score may increase, raising the amount of Decarbonization Credits (CBIO in Portuguese) that can be marketed, reinforcing biofuel production as well [39]. The National Agency of Oil, Natural Gas, and Biofuel is establishing criteria and procedures for the generation of information necessary to guaranty the issuance of CBIOs [40].

Bioelectricity from biogas has almost doubled since 2011, but this fuel remains a minor factor in the country's generation capacity, despite its potential for growth. In 2011, Brazil had only 13 biogas plants, with a total of 69 MW in installed capacity. By 2019, there were 39 plants (among agricultural residues, animal residues, and urban solid waste),

increasing the capacity to 167 MW [30].

Growth in biogas generation is expected to occur more rapidly in the second half of this decade, when the National Solid Waste Policy [41] is eventually adopted by states and municipalities. The law sought to eradicate the utilization of open landfills across the country by pushing local governments to build and approve solid waste plans, including targets to recover energy from waste by 2014. However, most of the states and municipalities have not written and approved such plans in their local councils, forcing the federal government to push the deadline to 2021 [42]. Few adjustments have been made so that solid waste is disposed only in sanitary landfills, with approximately 40.9% of all the waste collected in the country is disposed in inappropriate places [43, 44]. This scenario, however, highlights a great potential for solid waste power generation.

The PROBIOGÁS, a Brazil-Germany project to promote the utilization of biogas energy, is crucial for the implementation of the National Plan for Basic Sanitation, PLANASAB, which seeks to foster the energy use of biogas from sanitary sewage and solid waste treatment processes. Recent initiatives of medium to large biogas generation plants from organic fractions are emerging, with sequential batch methanation tunnels (SBMT) as a promising technology for the national scenario due to the legal conditions and the characteristics of the available substrate [45]. The first SBMT extra-dry treatment plant in Latin America, located in Rio de Janeiro, was inaugurated at the end of 2018 [46].

#### 3.2.2. Liquid biofuels transport sector

The national action plan seeks to expand the consumption of biofuels as well as to increase the supply of ethanol and the participation of biodiesel in the diesel mixture [10], reaching a total of 10% (B10) by 2019 (Law No. 13.263/2016) [47]. Biofuels represent a milestone of success in Brazil's energy policy since the oil shock in the early 1970s, when the National Alcohol Programme (PROÁLCOOL) was designed to reduce the country's dependence on imported fossil fuels by incentivising the production of ethanol from sugar-cane [48].

Initially, to fuel a national fleet of ethanol-only vehicles, the programme was later adapted to the nascent flex-fuel vehicle market based on the mandatory additions of 27.5% ethanol to gasoline [49]. As a result, Brazil became the world's second largest ethanol producer, with an output of 33.14 billion litres in the 2018/2019 harvest, following 60.9 billion litres in the USA [19]. Ethanol production is still primarily (95.8%) derived from sugarcane<sup>3</sup> [50]. In addition, low global sugar prices, ethanol production also benefited from lower federal taxes and rising global oil prices, which offered a price advantage and contributed to an increase in the domestic demand [19].

Biodiesel followed a similar pathway, driven by a mandatory 2% biodiesel mixed with fossil diesel, enacted in 2005, which was later expanded to 10%. Currently, this percentage is expected to increase by 15% by 2023 by Law No. 13.263/2016 [47]. Again, the legislation led the country to become world's second largest producer of biodiesel (with an increase of 13% between 2017 and 2018, totalling 5.3 billion litres in 2018), behind the USA (6.9 billion litres) [19]. Unlike the ethanol market, feedstocks vary more widely for biodiesel, which is mostly produced from soy oil (67% of the biodiesel total), animal fat (14.8%), and oily seeds (3.8%), among other minor sources [51].

The new National Biofuels Policy [38] aims to expand biofuel production in Brazil. This policy is based on the following strategic axes: discussing the role of biofuels in the energy matrix; developing fuels based on environmental, economic, and financial sustainability; marketing new biofuels to gain attention. Therefore, RenovaBio has set national targets for reducing emissions in the fuel matrix, broken down into individual annual targets for fuel distributors according to their

<sup>2</sup> The targets specify that hydropower shall correspond to at most 17% of Brazil's total energy mix by 2030, compared with the current 12.6% [37].

<sup>3</sup> The Biofuture Platform is a 20-country effort led by Brazil to promote an advanced low-carbon bioeconomy that is sustainable, innovative, and scalable [54].

share of the fossil fuel market. RenovaBio is set for a period of 10 years (Table 5), with a drastic expected reduction in GHG emissions from the fuel matrix of 686.3 million tons CO<sub>2</sub>eq during this the period, approximately 57% of the Brazilian NDC (1.2 GtCO<sub>2</sub>eq GWP-100 in 2030) [10].

Biofuel production facilities are undergoing certification, with grades that are inversely proportional to the carbon intensity of the biofuels produced, reflecting the individual contributions of each producer to GHG mitigation (in terms of tons of CO<sub>2</sub>eq). The interaction between these two instruments will be performed through the CBIO, which is an exchange-traded financial asset issued by the biofuel producer to be used as a demonstration of compliance with the individual targets (Fig. 2). The projected initial price of the CBIO is 10 USD.

Finally, the second-generation biofuel market is just beginning to develop, despite the widespread availability of feedstock and potential to generate added value to the abundant agricultural and forestry residues. In our previous work [22], we highlighted the potential upsurge in Brazil's microalgae biofuel production if technological and economic barriers were overcome with R&D efforts. However, R&D has since slowed largely due to the economic downturn, and the technology remains in the pilot demonstration stage.

Our current assessment indicates that it is unlikely that this technology will advance toward significant commercial deployment in Brazil within the NDC horizon. However, Brazil's recent leadership in the Biofuture Platform<sup>4</sup> indicates that second-generation biofuels should be a major focus area for innovation investments in the coming years, aided by an emphatic government and private support in R&D to realise this potential. However, it is unlikely that advanced biofuels will correspond to more than 5% of Brazil's biofuel target specified within the NDC.

For the transport sector, Brazil and other 70 countries established some form of biofuel policies by the end of 2018 [19]. Interestingly, most of these policies are focussed on first-generation biofuels, ignoring second-generation fuels in Brazil and globally. Brazil has operated with soft policies, such as the National Energy Policy Council's Resolution n. 14, which determines that policy makers should recognise the capacity of biofuels to decarbonise the transport sector when defining policies to incentivise biofuels [55].

Overall, Brazil could easily achieve its NDC target of bioenergy comprising 18% of the country's total energy consumption by 2030, given that sugarcane sub-products are already responsible for 17% of Brazil's total energy consumption [23].

### 3.2.3. Biomass-generated heat – residential and industrial sectors

Solid biomass is primarily utilised for heat generation in the residential and industrial sectors, including agriculture, all of which have different ongoing trends. In the industrial sector, the iron and steel industries use coal-coke as the main reducing agent for pig iron and iron-alloy blast furnaces. Charcoal represents a local alternative to offset some of the demand, especially when coal-coke prices are high as well as when it is used as an alternative to generate power in combined heat and power plants. The outlook for 2027 [23] shows that charcoal and firewood consumption in the industrial sector will remain steady over the next 10 years (from 11.8% in 2017 to 11.9% in 2027). The expected combined consumption of firewood (8.9 Mtoe) and charcoal (3.6 Mtoe) is projected to reach 12.5 Mtoe in 2027, 62% of the total estimated national consumption (20.1 Mtoe) for these fuels.

The residential sector utilised 10.6% (0.35 Mtoe) of Brazil's total charcoal consumption (3.33 Mtoe) in 2017 for heat and cooking [56]. However, the residential demand for biomass is forecasted to decrease given the expansion of using liquified petroleum gas as an alternative.

<sup>4</sup> BNDES seeks to incentivise the development of a local supply chain for renewable energy technologies by making technologies with a minimum local content (varying between 60 and 80% of technology value) eligible for subsidised finance [63].

Finally, the agricultural sector utilises 4.5% of Brazil's biomass for heating, particularly within the sugar-ethanol industry, where sugarcane bagasse satisfies all of the heat demand [37].

As described in the previous bioelectricity section, historical data indicate that the processes are increasingly efficient, reducing the bagasse demand for each product unit. In addition, as the industry increasingly deploys efficient units, less bagasse is required to fulfil the industry's heat demand, with the surplus available for commercialization or, most likely, incineration in power generation units.

### 3.3. Wind energy

Wind energy performed well in the last ten years in Brazil [28], reaching 15 GW of installed capacity across 614 plants in operation as of June 2019 [30], a sixteen-fold increase from the 0.94 GW in 2011. Another 49 plants are under construction and 144 are planned, adding 5.5 GW [30]. The industry has advanced considerably since 2011, with wind generation projects beating gas-fired generation in the annual lowest-price competitive auctions held by the government [57]. Highlights how the industry's first comers have been leading to the consolidation of a local supply chain, with global equipment manufacturers settling in Brazil to fulfil the National Development Bank's (BNDES) local content rules, which renders their products eligible for subsidised credit lines.<sup>5</sup>

This growth is expected to increase its share to 12% of the installed capacity of SIN in 2027, which, together with solar photovoltaic technology (with additional 5000 MW), will be responsible not only for maintaining the sustainable Brazilian electricity profile system but also for contributing to lower production costs in the future. The remarkable participation of wind energy in the Brazilian energy network helps to meet the increased demand for electricity with the difficulties related to the environmental licencing of conventional energy generation projects, such as hydroelectric and thermal [27].

Regarding the NDC horizon, some challenges to realising the country's wind energy potential remain. In particular, wind energy projects have been rejected due to the lack of adequate transmission lines, e.g. in the states of Rio Grande do Norte, Rio Grande do Sul, and Bahia, where estimated potentials are approximately 9.6 GW, 15 GW, and 100 GW, respectively [58–61].

Wind energy projects become less attractive to investors and for expansion plans when forecast scenarios indicate a limited energy demand due to the ongoing economic downturn. According to Ref. [62], Brazil has dropped in the ranking for renewable investments, which was aggravated by the cancellation of an energy auction in December 2016 due to the reduced prospective energy demand. Arrangements combining different technologies, such as photovoltaic and wind power plants, often referred as "hybrid power plants", should also be considered. However, this kind of sharing is not yet allowed by the current legislation.

Furthermore, the worldwide growth of the offshore wind sector was almost five times higher than the 2011 capacity, with 23 GW installed at the end of 2018. Although offshore construction is more complex, time-consuming, and expensive than onshore construction, the investment costs of offshore wind have been decreasing internationally, due to technological improvements, economies of scale, maturing supply chains, and better purchasing strategies. According to a recent World Bank study [64] that analysed Brazil and seven other emerging countries, India, Morocco, Philippines, South Africa, Sri Lanka, Turkey, and Vietnam, Brazil has immense potential for this sector. The study indicated that the countries have combined offshore wind total technical potential (measured in 200 km of coast) of 3.082 terawatts, with 1.228

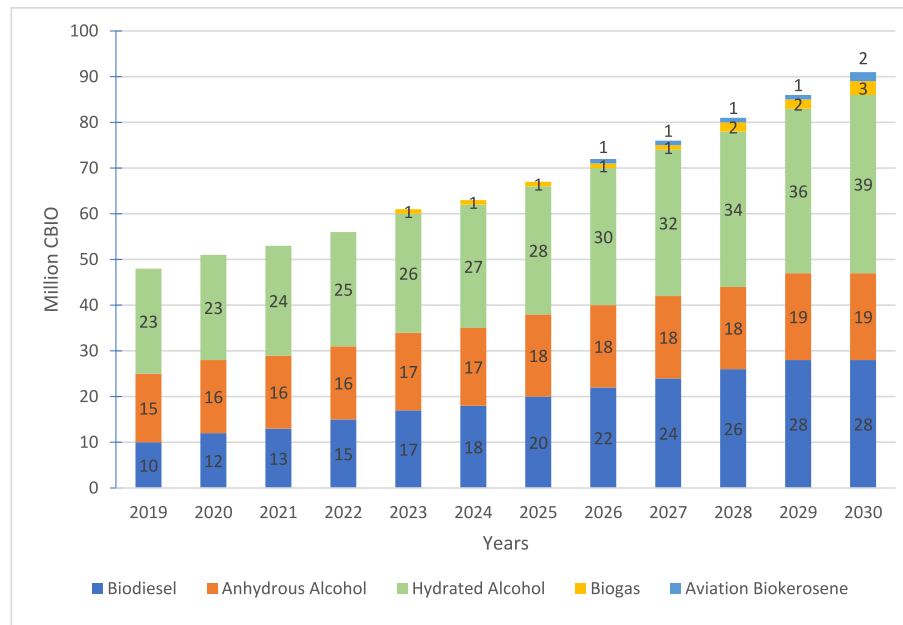
<sup>5</sup> Since 2004, the PRODEEM [66] installed more than 5 MW in PV capacity for water pumping systems, public lighting, and other rural community services, adding to over 9000 systems [57].



**Table 5**

Compulsory annual GHG reduction targets for the commercialization of fuels and the respective tolerance ranges, established in CBIOS [52].

Year	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
<b>Annual Goal (10<sup>6</sup> CBIOS)</b>	16.8	28.7	41.0	49.8	59.6	66.9	73.3	79.5	85.1	90.1	95.5

**Fig. 2.** CBIO offer projection for Biofuel [53].

terawatts in Brazil.

Studies carried out by Refs. [65] demonstrate the existence of a technical potential of approximately 700 GW in Brazil in locations with depths up to 50 m. The development of offshore technology brings numerous possibilities, such as the development of projects near the demand in large coastal cities, which reduces the investments in transmission and avoids the social impacts of onshore projects. However, it is vital to deepen the analysis using meteorological data and restricting the use of exploitable areas, such as environmental protection areas, commercial routes, migratory bird routes, oil exploration areas, or other areas of conflicting uses. Even with the indicated restrictions, the energy potential is sufficient for offshore wind farms to be considered as future options for the country [65].

Even with the energy potential, offshore wind is not expected to be deployed in Brazil in the NDC horizon because of the vast space available for onshore wind energy projects and the trend of increasing the turbine sizes before offshore projects become a viable investment option [57].

### 3.4. Solar

Solar PV systems have fallen short of the expectations set in Ref. [22] and have been gradually added to Brazil's grid since 2004<sup>6</sup>. Initially utilised to feed off-grid systems, PV was slow to be considered as a realistic option for energy generation, hindered by the technology costs and, hence, a long payback term [28].

Through Power Purchase Agreements (PPA) in 2018, dramatically low prices were observed in several countries, including Brazil (less than 30 USD per MWh). A considerable part of Latin America's installed capacity has been developed through large-scale PPA, with many new projects announced in 2018. Therefore, the distributed solar PV sector has begun to grow, particularly in Brazil, and the distributed capacity surpassed 0.5 GW in 2018. In total, Brazil added more than 1.1 GW in

2018, doubling its installed capacity to almost 2.3 GW [18].

Decentralised PV systems are becoming a feasible option for households, buildings, and businesses, encouraged by recent tax breaks in multiple states. In addition, this technology has been boosted by a regulation enacted in 2012 that obliges power utilities to accept and support decentralised generation systems into local grids. Decentralised PV systems are finally flourishing, albeit still limited by factors such as cost, the lack of a local supply chain, and the lack of network flexibility to accommodate its intermittent generation. A recent analysis has indicated a positive outlook, largely dependent on the impacts from the additional regulatory incentives. Decentralised PVs could reach 1–2 GW of installed capacity in 2024 and 9–15 GW in 2030 [67].

Currently, there is 2.26 GW of centralised PV capacity in operation, and almost 1 GW under construction [21]. Despite the challenges, probably larger than those restricting decentralised PVs [16], estimates that centralised PVs will correspond to 8.6 GW (5%) of Brazil's generation capacity by 2027.

The main challenges of centralised PV generation include: (i) technology costs, linked to the lack of a local supply chain, an unfavourable taxing system, a high cost of commercial finance, and exchange rate risks; (ii) regulatory limitations regarding subsidised financial mechanisms, for which only technologies with a high share of local content are eligible, which are scarce given the lack of a local supply chain; and (iii) a generally unfavourable policy and regulatory environment that renders Brazil unattractive for major PV developers [12,68].

Concentrated solar power systems for power generation were not mentioned as a significant technology perspective in Ref. [22], which is currently justifiable due to the limited R&D and pilot projects in Brazil. In addition, no upcoming generation projects are expected over the next 10 years. Solar water heaters, however, are a potential consolidated technology, especially since it became part of social housing projects early in this decade. Brazil's total installed capacity of cumulated water collector installations is 10,411 MW [69]. The biggest difficulty with the

large-scale use of solar heating systems in Brazil is associated with two main factors: lack of population awareness and relatively high initial investment compared with the most commonly used equipment, the electric shower [70].

### 3.5. Nuclear energy

Brazil's nuclear energy development has remained largely stagnant since 2011. An installed capacity of 2 GW, split across two power plants in the State of Rio de Janeiro, has been operational since the last decade and remains unchanged, while the prospect for a third unit on the same site has been postponed many times amidst corruption scandals and a downturn in the country's energy demand. The third unit would expand Brazil's nuclear capacity up to 3.4 GW, corresponding to 1.5% of the installed capacity forecasted by 2027 [23], similar to the 1.2% value represented in 2019 [30]. It should be noted that nuclear energy is not included in the NDC targets, but the technology could support significant reductions in GHG emissions.

### 3.6. Carbon capture and storage

Although CCS is regarded as essential to reach the IEA's 2 °C scenario, and despite Brazil's inherent potential for CCS projects, this technology has not yet met the expectations presented in Ref. [23]. In terms of technology advances, CCS in Brazil has not changed since the previous paper [22], although several new plants have emerged. Early in the global economic downturn in 2009, Petrobras publicly committed to store 100% of the carbon content of newly discovered pre-salt gas fields in geologic reservoirs, justifying the optimism in Ref. [22]. In fact, since 2015, one CCS facility has been operating in South America —Brazil's Petrobras Santos Basin CO<sub>2</sub>-EOR (enhanced oil recovery).

In December 2017, Petrobras reached a milestone of 7 MtCO<sub>2</sub> captured and reinjected into geologic storage sites. An annual CO<sub>2</sub> injection of 2.5 Mt was achieved by 10 floating production storage and offloading units —seven at the Lula field, two at the Sapinho field, and one at the Lapa field [71]. Nonetheless, Brazil's CCS plans are considered to be dormant, with no perspective of revival on a commercial scale for the next few years. Similar to nuclear power, CCS is not included in the NDC targets, but the technology can aid GHG reductions.

### 3.7. Energy efficiency

Energy efficiency represents a significant proportion of opportunity in the pursuit of limiting global warming to a 2 °C, and it is globally acknowledged as a cost-effective way to mitigate emissions, strengthen energy security, and increase business competitiveness. While the global market for efficient technologies and services is thriving, Brazil lags behind despite the existence of efficiency opportunities throughout its sectors. In fact, efficiency has been a topic of Brazilian policy for over 20 years, with numerous federal plans, cross-sector programmes, and a number of sector-specific regulations. However, these initiatives have been partially successful with only a few programmes worth being highlighted.

- ANEEL's Energy Efficiency Programme (PEE) - Enacted by Law No. 9991/2000 [72], the PEE imposes a levy on electricity distribution utilities with a mandate to invest 0.5% of their net revenues in energy efficiency projects. When comparing the total energy saved in 2011 (382,869.77 MWh/year) to more recent years (5332.21 MWh/year in 2018), the energy saved dropped considerably. The programme also obliges utilities to invest at least 60% of the resources on efficient appliances for low-income households. The most recent amendment to this program (Law n. 13280/2016) [73] allows the utilities to decide whether to allocate resources to low-income households or not, with the results yet to be confirmed. However, this law appears to be correlated to the decrease in the total energy saved in 2016.

- National Programme for Electricity Conservation (PROCEL) -

Enacted in 1985 by the Ministry of Energy (MME) and executed by the state-owned power utility Eletrobras. PROCEL is a combination of sub-programmes to drive efficiency in multiple domains, namely, appliance labelling, buildings, education, public buildings, municipal energy management, industry, lighting, and sanitation. PROCEL's labelling efforts, assigned to the best performing equipment under the PBE, are renowned among consumers. The label has reaped significant results since its inception and helped save approximately 21 TWh/year in 2017 [75].

- The National Programme for the Rational Use of Oil and Gas Products (CONPET) - CONPET has existed since 1991 and provides voluntary labels to communicate the relative combustion efficiency performance of fuel-consuming equipment, classified into categories A to E [76]. Coordinated and executed by Petrobras, CONPET achievements in the industry and transport sectors are significant, with most large equipment manufacturers, virtually all vehicle and tyre manufacturers to voluntarily apply for the label. While there is no official publication of the CONPET results, adherence across the industry is a clear indication of the programme's relevance.

- Equipment Labelling Programme (PBE) - Enacted by Law n. 10925/2001 [74], Brazil's equipment labelling programme provides mandatory labels to communicate the relative efficiency performance of certain equipment to consumers, with categories ranging from A (most efficient) to E (least efficient). Delivered by a consortium between the national metrology testing network (INMETRO) and state-owned companies, Petrobras (within CONPET) and Eletrobras (within PROCEL), the label is used widely across electricity and fuel combustion equipment used in households and industry. There is no published data on the PBE results.

Considering Brazil's NDC, where a target to increase electric efficiency by 10% by 2030 is presented (against an optimistic baseline set before Brazil's economic downturn). The NDC does not mention thermal efficiency, which could provide a substantial energy saving opportunity, as shown in Table 1. Delivering this NDC target is, therefore, relatively easy, but indicates that the efficiency targets in Brazil could be much more ambitious.

## 4. Main findings

This section presents the primary findings on the analysis of the current situation and the prospects for low-carbon technologies, as shown in Table 6. The participation of renewables in the Brazilian energy mix will remain significant, with 47% composed of wind, solar, biomass, and hydroelectric energy, including small hydro, by 2027. Additionally, beginning operations at the Angra 3 nuclear plant and substituting natural gas into thermoelectric plants powered by diesel and fuel will be able to remove approximately 3000 MW of fossil sources from the energy matrix by 2027 [23].

Low economic growth has led to a low demand for primary energy, and, consequently, the participation of oil, gas, and coal in the country's energy mix reached the lowest level in six years [79]. Although, renewable energy sources in Brazil experienced a significant jump in 2018, mainly due to wind and solar energy growth. Moreover, the country is currently in a difficult socioenvironmental-economic-political environment, driven by national and global instability and economic crises.

Regardless of the strategy and political policies of the current government related to global changes, the record energy auction prices, driven by the lower photovoltaic panel prices and intense competition, increase the consolidation of the renewable sources sector. Perhaps this is one of the most vital factors to consider, not only for the long-term energy planning for the country but also the diversification of the energy matrix through renewable energy projects, to solve the restrained demand issue when the country starts to grow again.

Table 7 shows a synthesis of the authors' considerations on the main bottlenecks and their likelihood of being widely deployed by 2030. The definition of main bottlenecks, comments, and likelihood of deployment

**Table 6**

Main findings on analysis of the current situation and the prospects for low-carbon technologies.

	Main findings
Hydropower	Hydropower installed capacity has increased by 36% since 2011 and is shifting towards “run of the river” type and small hydro, which are, <i>a priori</i> , less prone to causing environmental and social impacts. In addition, a vast potential for small hydro is available and Brazil is seizing it given the market maturity. Small hydro plants will play an important role in the achievement of the NDCs.
Bioelectricity	Sugar-cane bagasse bioelectricity has developed modestly since 2011, despite the enactment of RenovaBio. This law induces the efficiency increase in sugar-energy production units, increasing the amount of decarbonization credits, which can be traded in order to promoting the growth of the sector.
Biofuel	Brazil will remain a bio-fuel powerhouse and easily achieve the modest NDC target to render bioenergy responsible for 18% of the country's final energy consumption by 2030.
Biomass generated heat	Brazil is a global leader in the utilization of renewable heat —primarily due to the iron and steel sector's utilization of planted forests for charcoal production, which is a substitute for mineral coal. Biogas-fuelled power plants are developing slowly despite the enormous potential available from municipal solid waste, industrial, agricultural, and livestock residues.
Wind Energy	Wind power is developing rapidly; responding to the early signs of a local supply chain, but still has room for substantial growth and should greatly contribute to meeting the NDC goals, surpassing 27 GW in installed capacity by 2027.
Solar	Solar power is developing slower than what was expected in 2011. Prospects for decentralised PVs are finally improving, boosted by the first signs of a local supply chain, regulatory improvements, and state taxes exemptions. However, centralized PVs remains mostly unattractive to investors, and will require more support if such power plants are to significantly contribute to the NDC target.
Nuclear Energy	Nuclear energy plays a relatively marginal role in Brazil's power sector, and its contribution will remain stable. Nuclear energy is not part of the actions accepted by the UNFCCC for GHG reductions despite not emitting GHGs.
CCS	CCS is not expected to be deployed commercially in the next few years. Additionally, CCS has not yet been officially accepted by the UNFCCC and is not part of the NDCs or the Paris Agreement. Although, it is considered to be valuable by the IPCC and as a technology that can compensate for carbon emitted. It is a promising technology with beneficial pilot projects, but is still developing in terms of scale.
Energy efficiency	The NDC's energy efficiency target is likely to be achieved due to its modesty but is not an ambitious reflection of the potential for energy savings in the country. This potential is hindered by complex barriers that limit the formation and financing of a pipeline of projects. Despite numerous policies and initiatives with some relevance for energy efficiency, there are no clear prospects for a change in this market. Another strategy suggested by Ref. [78] is the participation in climate clubs, such as the International Solar Alliance, which can help to lower the barriers to a higher penetration of renewable energy and energy efficiency, and even position Brazilian bioethanol as a global commodity.

Source: Prepared by the authors.

for each technology (among low, medium, or high) was based on informal interviews among authors, collaborators, and other specialists within each technology.

## 5. Conclusions

This paper offers perspectives for low-carbon energy technology development in Brazil, pinpointing significant changes that have occurred since our former publication in 2011. The paper also provides an updated likelihood that Brazil will achieve its NDC commitments in the energy sector. In 2011, there were no NDCs and the Paris Agreement, which have now become the new metric for target comparison in this paper. Globally, unless governments increase their ambition, the collective effort of the current national policies significantly will fail to achieve the objectives of the Paris Agreement and even to meet the joint ambition secured in the NDCs. The results have strong implications beyond 2030 [1].

Previous literature has shown that inadequate near-term reduction efforts imply that a substantially higher rate of transformation will be needed to comply with the 2 °C limit [80,81], stranded assets [82], and substantially higher mitigation costs in the long term [83]. Despite a series of barriers that impede the development of some technologies, along with an ongoing economic downturn, Brazil is on track to assume its global commitments, especially because its energy system (mainly the electric and transportation sectors) has the potential to be the least carbon intensive in the world.

The perspectives for some of the technologies analysed are in accordance with the NDC horizon. However, low-carbon technologies could be deployed well beyond the NDC targets, given the country's abundance of natural renewable resources. In addition, the prospects in Brazil's official energy plan for 2027 are very much aligned with the IEA's RTS scenario. Therefore, the focus should remain on technological developments. In addition, it is necessary to remove barriers stopping specific technologies (as well as possibly inserting incentives to technology deployment where needed) in order to ensure the achievement or surpassing of the NDC targets.

Brazil has one of the cleanest energy arrays around the world. An energy matrix that emits less and less GHG implies an increasing

participation of renewable sources, which, in general, are more vulnerable to climate change. In this context, the challenge for the sector is to guarantee the security of the system. One crucial question that arises is how to speed up implementation to achieve the NDCs and increase the ambition to stay on track to meet the well-below 2 °C goals. The current policy implementation is weak and includes significant gaps. Moreover, it is often fragmented in terms of the use of policy instruments and the coverage of sectors and countries. A redesign of the current policy consisting of more coherent policies would be desirable, such as a more efficient integration between the sectors of the water-energy-food nexus aligned to the NDCs [84], both within Brazil and globally.

Additionally, the health, humanitarian, social, and economic crises set off by the COVID-19 pandemic have impacted the energy sector worldwide. Although the full impact on the energy sector is difficult to predict, a decreased energy demand, plummeting energy prices, and a decline in oil prices have already been observed. The global energy transition may also be affected [85]. In Brazil, no direct measures or policies have been observed to date to combat the effects of COVID-19 in the renewable energy sector. Therefore, it will be important to develop measures, policies, and research in order to leverage the progress achieved with renewable energy and not lose sight of the efforts needed to reach the objectives of the Paris Agreement and the 2030 Agenda for Sustainable Development.

Furthermore, renewable energy must play a key role in economic recovery, ensuring sustainability and energy security, creating jobs, and strengthening resilience to protect people's health and welfare. No other industry can match such an impact while simultaneously reducing global climate emissions [85]. In response to the crisis, governments are currently in a position to recognise the benefits of renewables, continue to build broad public support for the transformative decarbonization of societies, and pave the way for a clean, low-carbon economy.

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**Table 7**  
Perspectives for low-carbon technology deployment in Brazil by 2030.

Technology	Key bottlenecks	Likelihood of wide deployment by 2030	Additional Comments
Run-of the river hydro power	Costs/susceptible to water level variations/socio-environmental conflicts	Medium	The last large hydro plants built in Brazil, in Madeira River and Belo Monte, are the “run of the river” type. The advantage is less environmental impact; the disadvantage is a poor use of the hydro energy potential.
Small hydroelectric plants	Initial investments/possible land use conflicts	High	The expansion of small hydro must consider the situations where small hydro plant construction generates possible cumulative and synergistic socio-environmental impacts.
Liquid biofuels	Land use conflicts/logistics	High	In the case of Brazil, ethanol from sugar cane is still the most important in scale of production. Replacement by liquid biofuels result in the reduction in the net GHG when there is a cycle to compensate for the carbon emissions of biofuel combustion. We highlight the initiatives already mentioned, such as the Biofuture Platform.
Solid biomass (electricity)	Lack of financial incentives/logistics/costs of new technology/cultural inertia	High	We highlight high potential for producing electricity from sugarcane bagasse and the perspectives of RenovaBio.
Solid biomass (iron/steel)	Lack of control over deforestation charcoal/higher costs for reforestation charcoal/logistics	Medium	There are potential for new types of solid biomass such as pellets.
Biogas	Technological upgrade lag/costs	High	Recent initiatives of medium to large biogas generation plants from organic fraction are emerging, with the Sequential Batch Methanation Tunnels as a promising technology.
CCS other	Higher costs/lack of incentives and regulation	Low	Necessity for regulation and monitoring the carbon emissions from the plants. It is considered promising by the IPCC but with reduced-scale pilot prototypes. It is not yet part of the projects accepted by the UNFCCC to reduce GHGs, even though it does not emit GHGs. Therefore, it is not part of the NDCs nor the Paris Agreement.
Power generation efficiency and fuel switching	Costs/lack of incentives	Medium	The power generation efficiency, independent of the fuel source, results in less natural resource demand. In an economic crisis, projects of energy efficiency are critical and more easily implemented.
Nuclear energy	Social conflicts/NIMBY syndrome/regulatory delays	Medium-high	In addition to environmental risks associated with nuclear energy, the construction of the Angra 3 plant is under anti-corruption investigation. It is not yet part of the projects accepted by the UNFCCC to reduce GHGs even though it does not emit GHGs. Therefore, it is not part of the NDCs nor the Paris Agreement.
Wind energy	Lack of investments in transmission lines and the economic crisis	High	Wind energy projects have been rejected due to the lack of adequate transmission lines. Offshore wind is not expected to be deployed in Brazil in the NDC horizon, given the vast space available for onshore wind energy projects.
Solar photovoltaics	Costs per MWh/cultural inertia/lack of incentives and national production	High	The public and private sectors reflect the creation of the solar photovoltaic industry in the country and the consequent expansion of this energy's usage.
Transport sector efficiency	Technological delay/costs	Medium	Need for investment in the individual awareness and public transportation investments.
Transport sector fuel switching	Associated land use conflicts/fossil fuel lobby	High	The transport sector is one of the largest consumers of energy. Any change in this sector has a major impact on the economy and the environment, as expected with the use of electric vehicles. Significant investments are necessary for the continuation of research for the substitution of fuels in the transport sector.

Source: Prepared by the authors.

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### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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technologies in Brazil for the next ten years.

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